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REAL TIME THERMOREGULATORY MODEL FOR EXTREME COLD STRESS: APPLICABLE TO OBJECTIVE FORCE WARRIOR (OFW)

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USARIEM TECHNICAL REPORT T03-05

REAL TIME THERMOREGULATORY MODEL FOR EXTREME COLD STRESS: APPLICABLE TO OBJECTIVE FORCE WARRIOR (OFW)

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13. ABSTRACT *(Maximum 200 words)*
A mathematical model for predicting shivering and thermoregulatory responses during long term cold exposure has been developed and validated. The basis for this model is a six-cylinder mathematical model of human temperature regulation which was well validated (Xu and Werner, Appl. Human Sci. 16:61-75, 1997) for dynamic conditions: incorporating heat, cold (less than 2 hours), clothing systems, and exercise. To what extent shivering is maintained over a long duration is not clearly known and a modeling technique has been sought to predict such responses. A new conceptual model for control of shivering intensity that takes into account the shivering endurance, inhibition due to a low core temperature and maximal shivering capacity was proposed. This conceptual model was further incorporated into the six-cylinder model to extend its capacity to long term cold exposure. The individual characteristics were defined as height, weight, fat percentage, age and VO2 max in the new model. The new model was validated against three test cases: 10 individual subjects who were immersed in 8-10°C water for 2 to 6.5 hours, a group of 9 subjects who were exposed in 5°C air for 3 hours, and 6 people who were involved in a shipboard accident and immersed in 16.7 °C water for 7 to 38 hours. The comparison has shown that the model predictions of the core temperature, mean skin temperature and shivering response to water immersion results were reliable within root mean square deviations of ±0.8C°, ±1.9°C, and ±47.2W, respectively. This model is applicable for cold stress predictions including Objective Force Warrior scenarios in its present form.

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EXECUTIVE SUMMARY

A mathematical model for predicting shivering and thermoregulatory responses during long term cold exposure has been developed and validated. The basis for this model is a six-cylinder mathematical model of human temperature regulation which was well validated (Xu and Werner, Appl. Human Sci. 16:61-75, 1997) for dynamic conditions: incorporating heat, cold (less than 2 hours), clothing systems, and exercise. To what extent shivering is maintained over a long duration is not clearly known and a modeling technique has been sought to predict such responses. A new conceptual model for control of shivering intensity that takes into account the shivering endurance, inhibition due to a low core temperature and maximal shivering capacity was proposed. This conceptual model was further incorporated into the six-cylinder model to extend its capacity to long term cold exposure. The individual characteristics were defined as height, weight, fat percentage, age and VO_2 max in the new model. The new model was validated against three test cases: 10 individual subjects who were immersed in 8-10°C water for 2 to 6.5 hours, a group of 9 subjects who were exposed in 5°C air for 3 hours, and 6 people who were involved in a shipboard accident and immersed in 16.7 °C water for 7 to 38 hours. The comparison has shown that the model predictions of the core temperature, mean skin temperature and shivering response to water immersion results were reliable within root mean square deviations of ±0.8C°, ±1.9°C, and ±47.2W, respectively. This model is applicable for cold stress predictions including Objective Force Warrior scenarios in its present form.

KEY WORDS: model, thermoregulation, shivering, cold, survival

INTRODUCTION

Predictive thermal modeling is useful for understanding of human responses to various environments, especially thermal extremes (i.e. long exposure to cold air or water). The models are valuable for predicting thermal responses and core temperature changes under conditions that cannot be tested ethically using human volunteers. Thermal models can be used to analyze possible scenarios for rescue organizations, cold accidents, post mortem criminal investigations or legal actions.

Objective Force Warrior (OFW) requires the use of a multidimensional model that allows physiological predictions over wide environmental and work level scenarios. However, predictive models for long-term exposure to cold are very limited, because of the lack of information on human responses to these conditions for extended periods of time. Most of these original thermoregulatory models' predictions are extrapolated to conditions of deep hypothermia (Hayward and Eckerson 1984; Wissler 1985; Tikuisis 1989; Van Dorn 2000). These models also do not fully consider shivering exhaustion. This factor is very important towards arriving at a description of balance between heat production and heat loss over a long duration. Tikuisis (1995) has developed a shivering exhaustion model and incorporated it into a one cylinder model of the human thermoregulation. This model can predict survival time of prolonged cold exposure. However, this model does not consider regional differences in the body (e.g. composition, blood flow, etc.) and their influences on temperature regulation. Other thermoregulatory models are also not able to predict the temperature of extremities which are critical to predict the human performance under extreme conditions (Stolwijk and Hardy 1977; Kraning and Gonzalez 1997).

A six cylinder model of human temperature regulation was developed by Xu and Werner (1997). This model has been well validated under conditions of heat, cold (maximum of 2 hours air), exercise, and clothing. Predictions of thermoregulatory responses from this model show that a steady state heat balance can be established after 3-4 hours of cold exposure and the steady state can be maintained as long as

shivering is not fatigued and suggest that it is necessary that shivering exhaustion should be taken into account in cold based models.

The purpose of this study is to conceptualize a model for control of shivering intensity using results from previous studies (Wissler 1985, Tikuisis 1995, Tikuisis and Giesbrecht 1999, Eyolfson et al. 2001) and to incorporate it into a six cylinder model (Xu and Werner 1997), so that the completed model will be able to predict future human responses to long term exposure to cold relevant to OFW needs.

METHODS

MATHEMATICAL MODEL

In Xu and Werner's model (Xu and Werner 1997), the human is subdivided into six segments consisting of the head, trunk, arms, legs, hands and feet. Each segment is further divided into the core, muscle, fat, and skin layer. The integrated thermal signal to the thermoregulatory controller is composed of the weighted thermal input from thermal receptors at sites distributed throughout the body. The difference between this signal and the threshold for each thermoregulatory function determines the function intensity. The method for prediction of shivering metabolism (M_{shiv}) requires modifications according to the following predictive algorithms and shivering exhaustion function. First, we describe the model for control of shivering intensity to aid conceptualization.

SHIVERING INTENSITY

Various aspects of the shivering response are defined and shown schematically in Fig. 1. Shivering increases metabolism above basal values (line A) according to the integrated thermal cold signal from core and skin receptors. Therefore predicted M_{shiv} would increase as core (T_{core}) and skin (T_{skin}) temperatures decrease (line B-B1) according to Tikuisis and Giesbrecht (Tikuisis and Giesbrecht 1999) until a maximal value (line C of Fig.1) is attained. Maximal M_{shiv} has been predicted to occur at skin

temperatures between 17-20°C (Benzinger 1969; Eyolfson et al. 2001), and is dependant on maximal aerobic capacity but inversely proportional to age and body mass index (BMI) (Eyolfson et al. 2001). Therefore the primary shivering response would be observed when T_{skin} ~ 20°C (line B-C), T_{skin} < 20°C with a constant low T_{core} (line B-D of Fig.1), or when T_{core} was gradually decreasing (line B-E). However, M_{shiv} may be lower than expected, secondary to either shivering inhibition (line F, when T_{core} < 32°C) (Tikuisis 1995) and/or shivering fatigue (line G, when metabolic substrates are limited) (Wissler 1985; Tikuisis 1995). This is defined as the secondary shivering response.

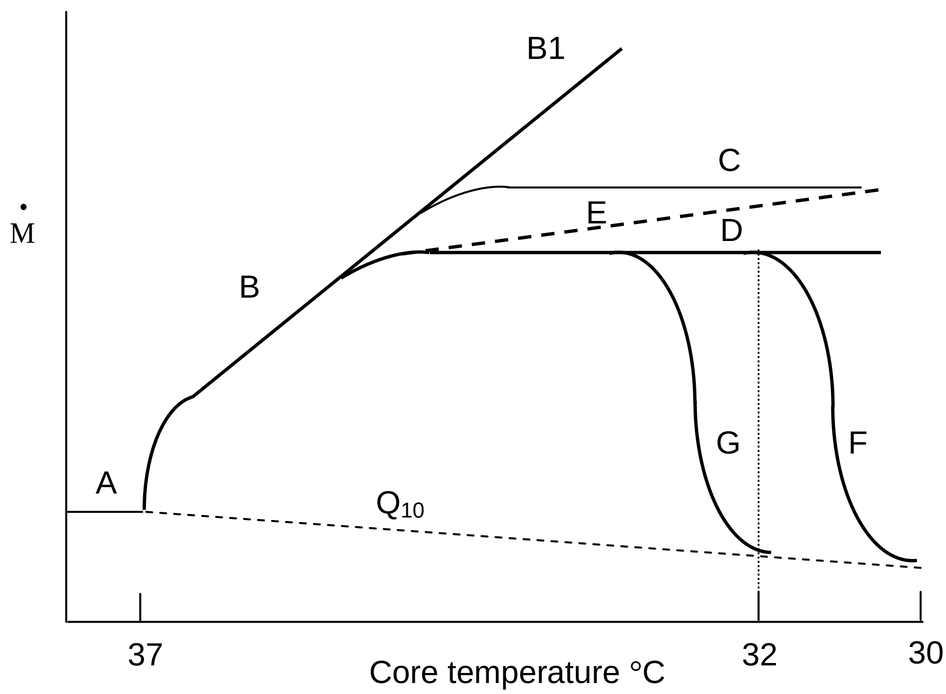


Figure 1. Conceptual model for control of shivering intensity. **A** – basal metabolism, **B** – predicted shivering intensity, **C** – theoretical maximum shivering intensity, **D** – observed shivering plateau when T_{skin}<20°C and T_{core} constant, **E** – observed shivering intensity as T_{core} decreases or T_{skin} nears 20°C, **F** – Thermoregulatory inhibition when T_{core}<32°C, **G** – shivering fatigue when shivering time exceeds the endurance time, $\mathbf{Q_{10}}$ – Tissue temperature/metabolism relationship in absence of shivering

METABOLIC HEAT PRODUCTION

The initial predicted shivering response (B-B1 of Fig.1) was calculated by the recent shivering algorithms derived from metabolic heat production data from three separate studies (Tikuisis and Giesbrecht 1999):

$$M_{shiv,i} = \frac{155.5\cdot(37-T_c)+47.0\cdot(33-T_s)-1.56\cdot(33-T_s)^2}{\sqrt{\%BF}} \quad (1)$$

where $M_{shiv,i}$ is the initial predicted shivering (W/m^2), T_c is the core temperature (°C), T_S is the mean skin temperature (°C) and BF is body fat percentage. The set points for core temperature and for skin temperature are adjusted to 36.7°C and 33.62°C respectively to fit into the original model. This equation is particularly suited for predictions involving long cold exposure, as the data included T_c as low as 33.23°C. Other prediction models only consider core temperature predictions $T_c \geq 35$°C (Tikuisis 1988, Stolwijk and Hardy 1977). The M_{shiv} cannot exceed the maximal shivering intensity (line C) which is estimated by a newly developed equation (Eyolfson et al. 2001):

$$M_{shiv,\max} = 30.5 + 0.348\cdot V_{O2\max} - 0.909\cdot BMI - 0.233\cdot Age \quad (2)$$

where $M_{shiv,\ max}$ is the maximal shivering intensity (O_2ml/min·kg), V_{O2max} is maximal O_2 consumption (O_2ml/min·kg), BMI is body mass index (kg/m^2), and Age is age in years. The calculation of Eq.1&2 will determine the primary shivering response ($M_{shiv,\ 1°}$)

The secondary shivering response (line F of Fig.1, $M_{shiv,2^o}$) due to thermal inhibition will be calculated by an empirical reduction factor defined by a hyperbolic secant function that smoothly and sigmoidally reduces shivering by a factor of 100 as T_{core} decreases from 32 to 30°C as follows (Tikuisis 1995):

$$M_{shiv,2^o} = M_{shiv,1^o} \cdot \sec h\left(2 \cdot \left(32 - T_c\right)\right)^{1.4} \tag{3}$$

When the core temperature reduces below 30°C, the shivering stops and the metabolic heat production changes according to Q_{10} effects (Tikuisis 1995).

Estimation of shivering exhaustion $M_{shiv,2}$ is presently based on a “glycogen-depletion” model (Wissler 1985) which assumes that time to exhaustion decreases exponentially as the intensity of shivering approaches a maximum value. There are two important calibration factors (α, β) in the method: α relates to when fatigue onset occurs; and β relates to how long it takes from fatigue onset to exhaustion. Shivering intensity will start to diminish as predicted by Wissler (Wissler 1985):

$$t_{end} = \frac{\alpha}{L_r} \cdot e^{-4.0 L_r} \tag{4}$$

where t_{end} is endurance time (the time until fatigue onset) in hours and L_r is shivering intensity:

$$L_r = \frac{M_{shiv,1^o}}{M_{shiv,\max}} \tag{5}$$

The value α is a calibration factor with a value of 18 that corresponds to observed shivering fatigue during shivering (Wissler 1985). This value was found to be satisfactory by a recent study (Tikuisis et al. 2002) where predicted shivering endurance time was compared with the water immersion tests.

As shown in Eq.(4)+(5), the t_{end} changes when shivering intensity varies. Tikuisis (1995) developed a method to account for this. The end of endurance is predicted when $\sum \frac{\Delta t}{t_{end}}$ equals unity where Δt is the time step and the t_{end} is the endurance time

corresponding to the shivering intensity during that time step. After shivering fatigue onset, i.e. secondary shivering due to fatigue (line G of Fig.1) is assumed to continue but at an intensity that is reduced by the following factor:

$$M_{shiv,2^o} = M_{shiv,1^o} \cdot \sec h \left\{ \frac{\frac{\sum \Delta t}{t_{end}} - 1}{\beta} \right\} \tag{6}$$

where β is the second model calibration parameter with a value of 0.38.

BLOOD FLOW TO MUSCLE

WIth vasoconstriction during cold exposure, there is a redistribution of blood away from the extremities and skin. This diminishes the heat loss from the core to the skin surface and eventually from the skin surface to the environment. Blood flow in the extremities of the calf and forearm is reduced from 3 ml/100ml tissue·min to near zero during cooling (Pendergast 1988). This reduction has been attributed to a reduced muscle blood flow (Durcharme et al 1991, Park et al 1984, Veicsteinas 1982). Alternatively, shivering demands more oxygen that is transported via blood flow. Therefore, the muscle blood flow during cold (i.e. a<0.0)is expressed as:

$$Q - Q_0 = \varepsilon \cdot a + (M_{shiv} + M_w) \cdot \xi \tag{7}$$

where Q (m^3blood/h·m^3tissue) is the muscle blood flow, Q_0 is basal muscle blood flow, ε (m^3/h·m^3°C) is a distribution factor for vasomotor activity in muscle, a (°C) is afferent signal for the controlling system, M_w (W/m^3) is extra metabolic rate due to exercise and ξ (m^3/h·W) is a constant. The ε ranges from 0.2 to 3.5 m^3/h·m^3°C for the six cylinders. This equation is implemented into the controlling system of the base model (Xu and Werner 1997).

RESULTS

The conceptual model and the equation for the muscle blood flow described above were integrated into the six-cylinder model (Xu and Werner 1997). The new incorporation was validated against the data available from experiments and from well-documented accident case reports. Three sets of data including water immersion, air exposure, and accidents of water survival were selected for the validation. Data from a recent water immersion experiments conducted at the University of Manitoba (Tikuisis 2002), involving immersion at 8°C-10°C water for 2-6.5 hours were used. Additional data from cold exposure experiments were taken from Vallerand's study (1993), involving 3 hours exposure in 5°C air. Finally, the accident scenario of water survival was adopted from Van Dorn's description in his paper (Van Dorn 2000), where 5 people were accidentally immersed in water at a temperature of 14°C for 7 to 38 hours.

WATER IMMERSION DATABASE

A group of 12 fit, non-smoking subjects participated in the water immersion trials. The subjects were 3 female and 9 males with a mean age 24.8years, body mass 71.7kg, height 1.75m, body fat 22.7%. The subjects, wearing only bathing suits, were immersed to the upper chest level in cold water at a temperature of about 8°C-10°C in a seated position with arms out of water for 2 to 6.5hours. The water was well stirred, initially set at a temperature of 20°C, and was subsequently lowered to approximately 8°C over 15 min by adding water and subsequently rewarmed (<20°C) to elicit a new constant submaximal shivering response. For a detailed description of this test, please see Tikuisis et al (2002).

The data from 10 subjects were selected to validate the present model. The other 2 subjects were not used because the water temperatures were not stable and changed from 8 to 20°C. The individual subject characteristics are shown in Table 1. The model was used to predict the thermal responses of the individual subjects to the water immersion. The inputs for each individual are height, weight, fat percentage, age,

maximal oxygen consumption, and water temperature. The measured core temperatures (esophagus, rectal temperature and tympanic temperatures) and mean skin temperature were compared with the predicted core temperature and the mean skin temperature, respectively. The immersion time, measured and predicted core temperatures, mean skin temperature and metabolic rate are summarized in Table 2.

Table 1. Subject characteristics and immersion water temperature

Subject	Gender M1F2	Age y	Weight kg	Height cm	BF %	VO_{2max} ml O_2 /kg min	T_{water} °C
JF	1	25	102.0	193	24.20	57.7	8.0
SV	1	21	78.5	172	26.60	44.3	8.5
JH	2	20	61.0	167	33.60	48.0	8.5
GG	1	40	83.3	183	23.40	48.6	10.0
DE	1	34	70.0	180	26.70	49.3	10.0
SC	2	26	52.2	161	28.60	53.6	10.0
TS	1	26	79.5	184	16.70	64.5	9.0
BT	1	23	63.0	165	14.90	55.8	9.0
GL	1	20	74.5	182	20.40	52.8	10.0
JK	2	19	70.5	172	32.40	44.4	9.0

Table 2. Measured and predicted core temperature, mean skin temperature and metabolic rate for10 subjects during 8-10°C water immersion trials

Subject	Immersion Time (min)	T_{es} °C	T_{ty} °C	T_{re} °C	T_{core} °C, p	T_{sk} °C	T_{sk} °C, p	M W	M W, p
JF	380	35.7	36.1	35.0	35.0	14.2	14.3	444.0	411.8
SV	250	35.4	35.6	34.7	35.1	16.8	14.7	327.0	314.4
JH	240	36.3	36.5	34.9	34.6	12.1	14.4	340.0	261.4
GG	200	34.8	35.3	34.3	35.5	18.5	16.0	323.0	335.9
DE	190	36.6	37.0	35.5	35.2	17.1	15.8	322.0	298.0
SC	180	34.7	34.9	34.7	34.8	15.9	15.0	302.0	246.0
TS	170	34.7	35.0	34.2	35.1	14.8	15.5	447.0	397.0
BT	160	34.7	35.3	33.1	34.6	19.3	15.6	404.0	378.2
GL	130	36.3	36.5	35.7	35.2	17.5	16.2	345.0	351.7
JK	120	36.5	36.8	36.3	35.5	16.7	15.1	342.0	253.7
Mean		35.6	35.9	34.8	35.1	16.3	15.3	359.6	324.8
SD		0.8	0.7	0.9	0.3	2.0	0.7	52.5	60.2

p: prediction.

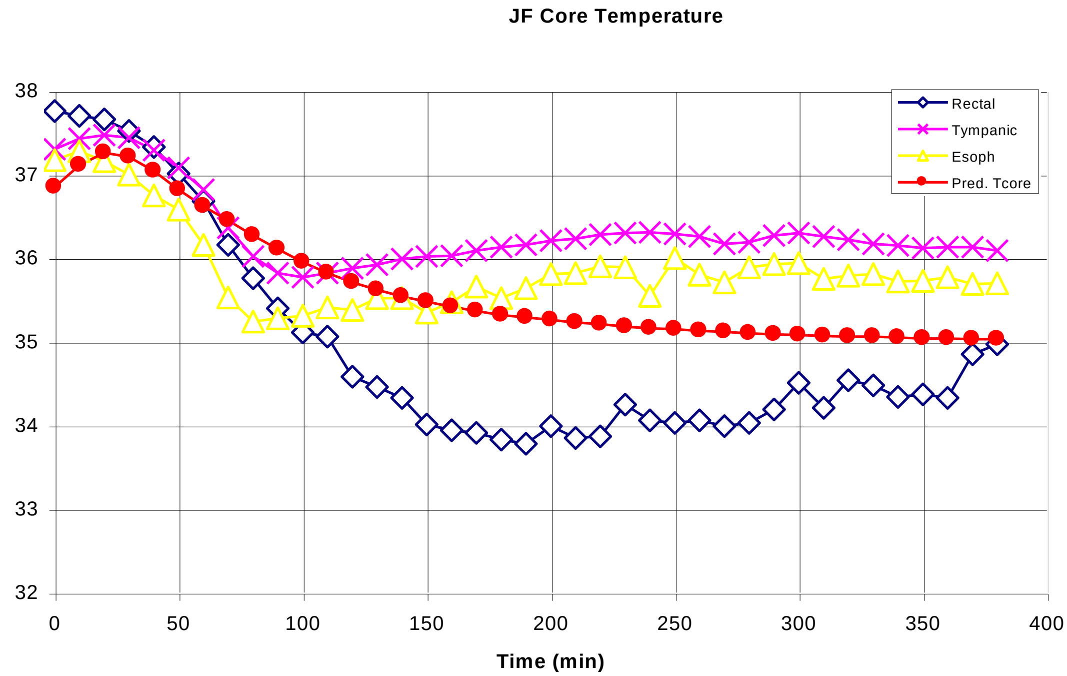
At the termination of water immersion (due to extreme discomfort), predicted core temperature of 9 subjects are either in the range of measured core temperatures or close to it within ±0.5°C. The predicted core temperatures of the other subject is 0.8°C below the measured value. A root mean square deviation (RMSD) of the differences between the observed and predicted at each available comparison points was defined by Kraning and Gonzalez (1997) to assess a model for “goodness of fit” quantitatively:

$$RMSD = \sqrt{\frac{1}{n}\sum_{i=1}^{n} d_i^2} \qquad (8)$$

where d_i is the difference between observed and predicted and n is the number of the comparison points. The RMSD of the core temperatures over 10 subjects is ±0.8C° during immersion period with an interval of 10min. The average predicted mean skin temperature is 1.0°C below the measured value within a RMSD of ±1.9°C. The average predicted metabolic heat production is 324.8W with a RMSD of ±47.2W, close to the measured value of 359.6W.

Of the 10 subjects, the predicted metabolic heat production of 8 were below the measured values. The values of the three females, i.e., JH, SC and JK were also well below the measured. While there is usually no gender difference in thermal responses to environments, the reason is very likely due to the fact that these three female subjects had high body fat percentage ranging from 28.6% to 33.6%. Although it is necessary to consider the body fat in the prediction of metabolic rate (Tikuisis et al. 1988), the Eq.(1) seems to overemphasize the impact of the adiposity on the shivering heat production for people with high body fat percentage. A recent study (Tikuisis et al 2002) attributed the underestimation of Eq.(1) for females to inappropriate weighting coefficients and/or too great attenuation of the shivering response due to body fatness.

Figure 2-11 shows the results of predicted and observed core and skin temperature for the 10 subjects. Overall, the predictions are close to the observation both in the trend and values for all subjects. It is interesting to note that the difference between observed core temperatures, i.e., esophagus, tympanic and rectal temperatures could be as high as 2°C.



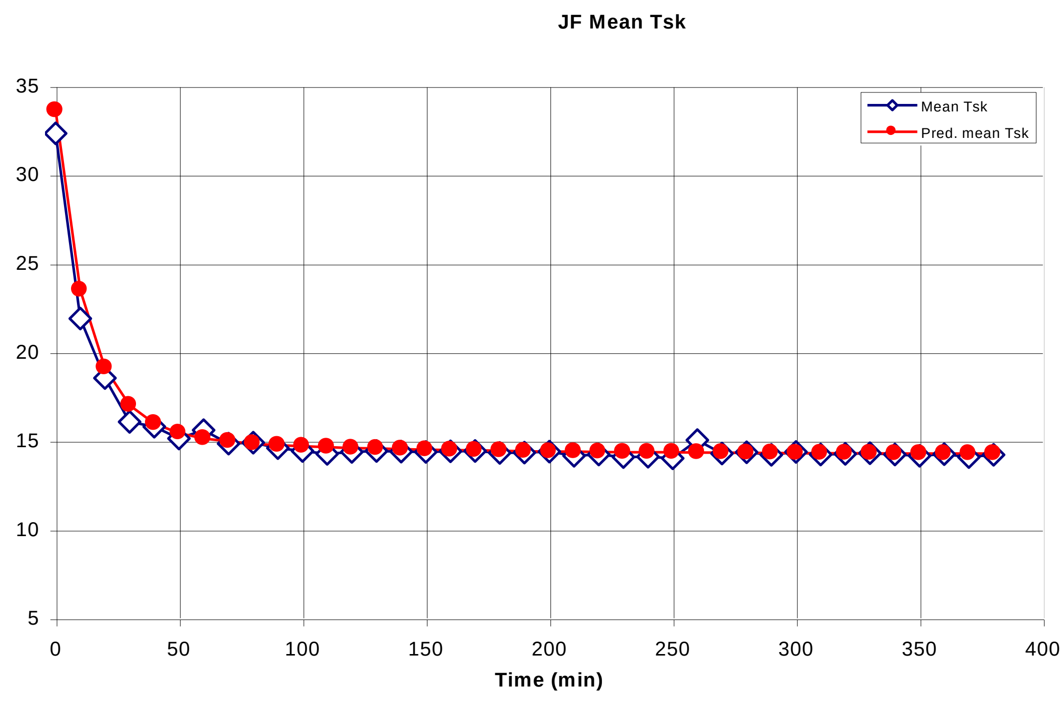


Figure 2. Experimental and predicted results during immersion in 8°C water for JF, Age 25, Height 1.93m, Weight 102.0kg, Fat24.26%, VO_{2max} 57.7 mlO_2/kg min

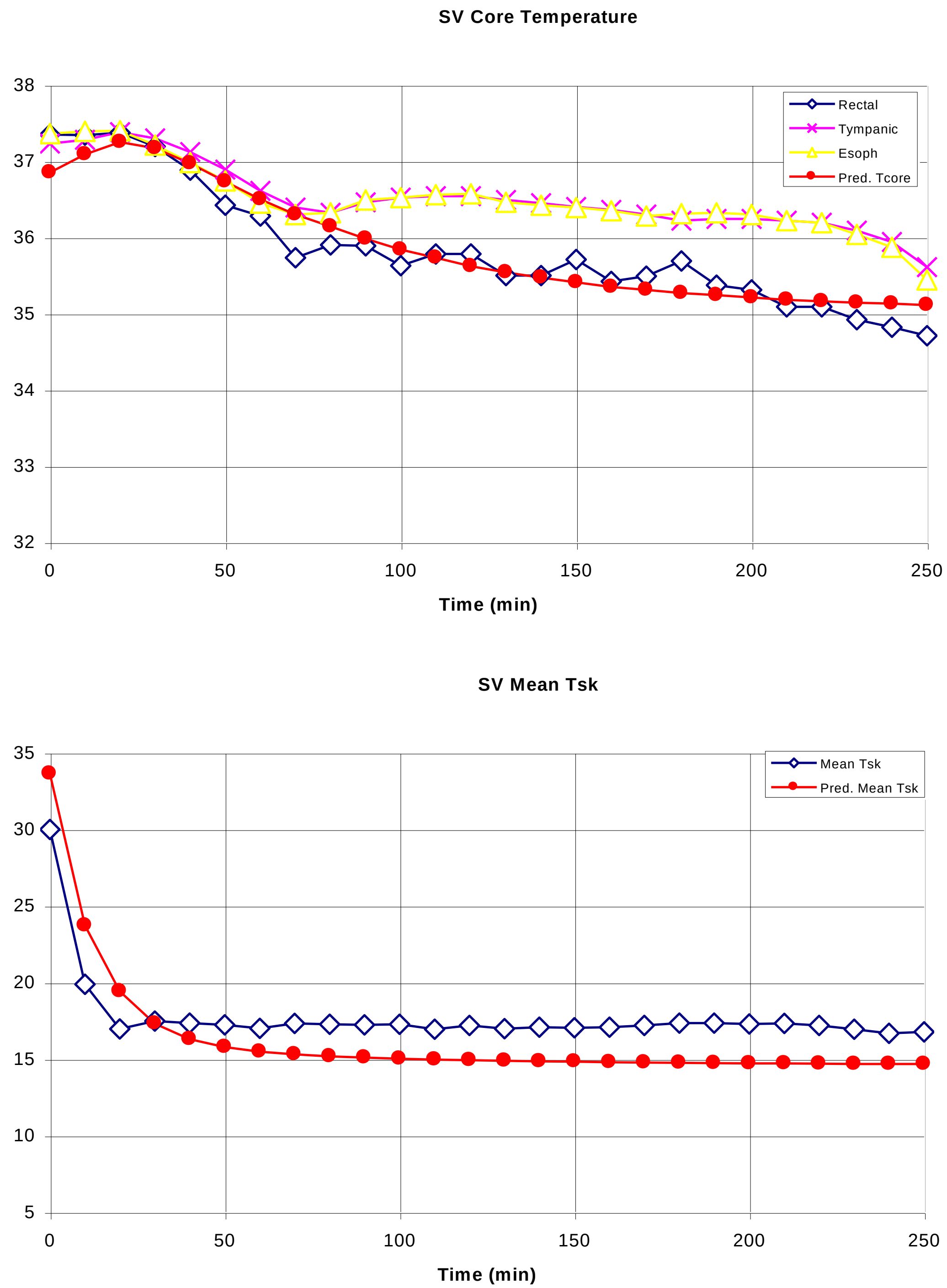
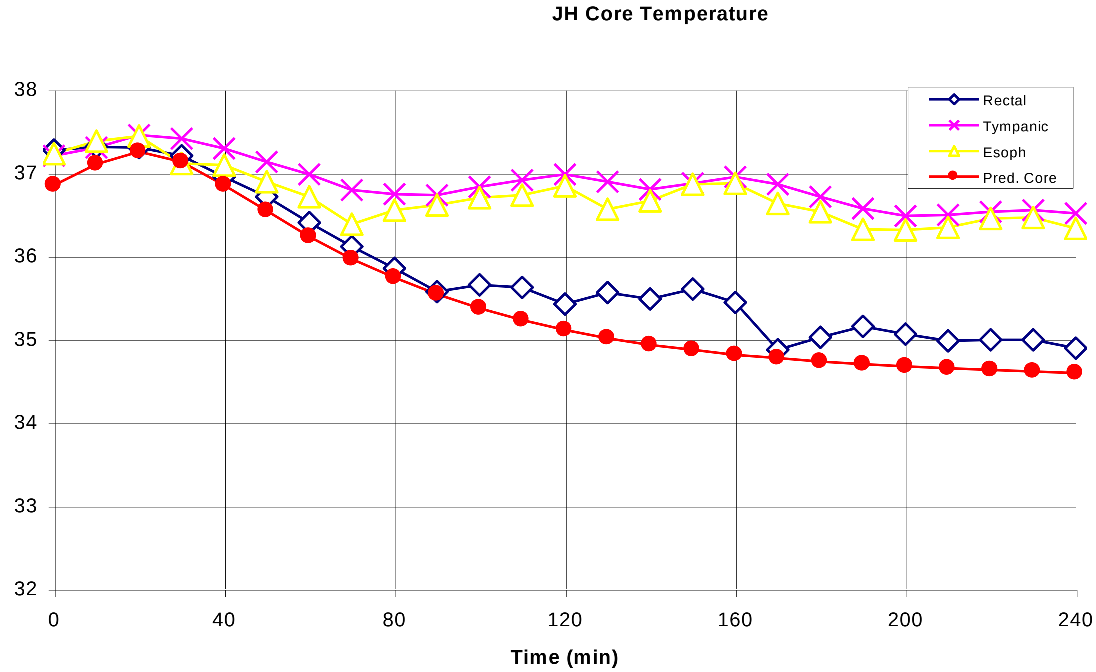


Figure 3. Experimental and predicted results during immersion in 8.5°C water for SV, Age 21, Height 1.72m, Weight 78.5kg, Fat 26.6%, VO_{2max} 44.3 mlO_2/kg min



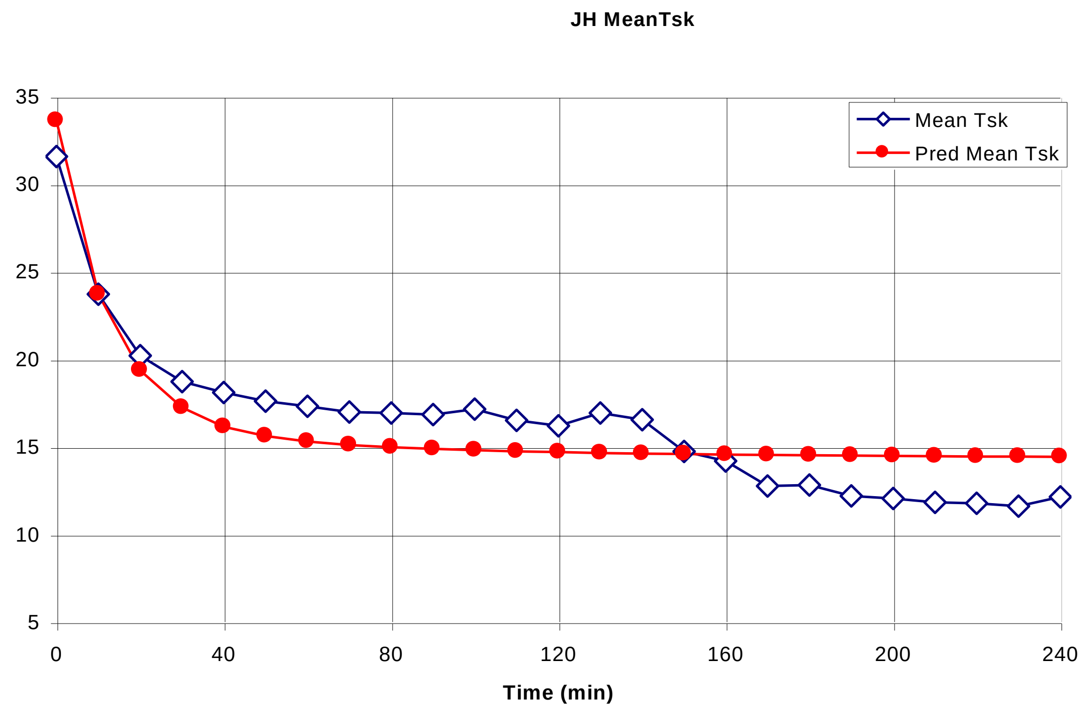
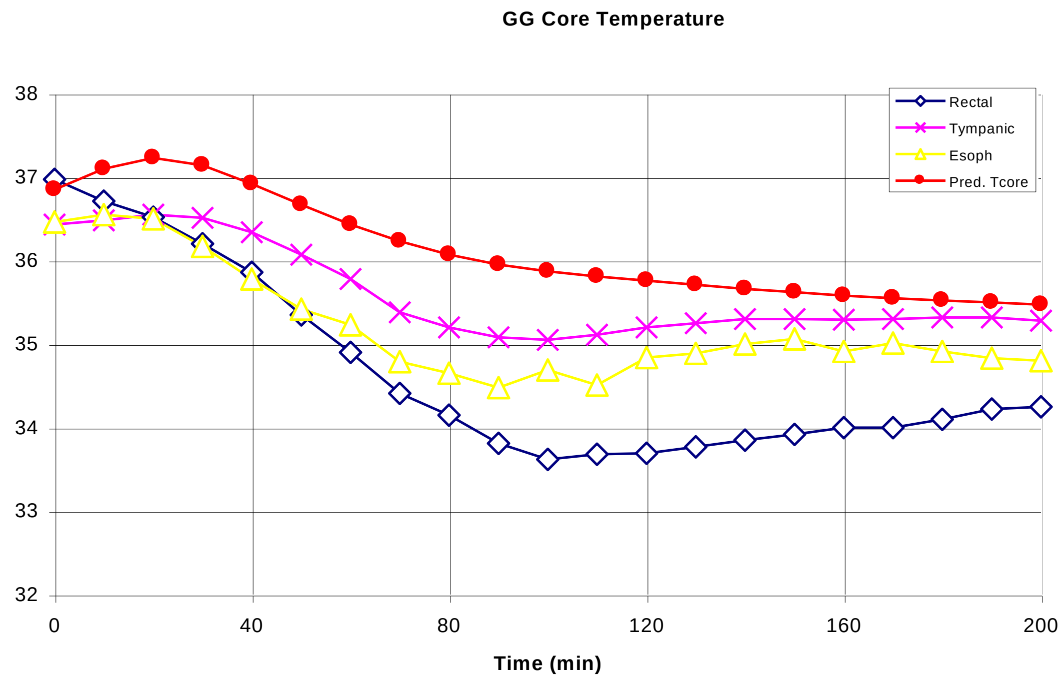


Figure 4. Experimental and predicted results during immersion in 8.5°C water for JH, Age 20, Height 1.67m, Weight 61.0kg, Fat 33.6%, VO_{2max} 48.0 mlO_2/kg min



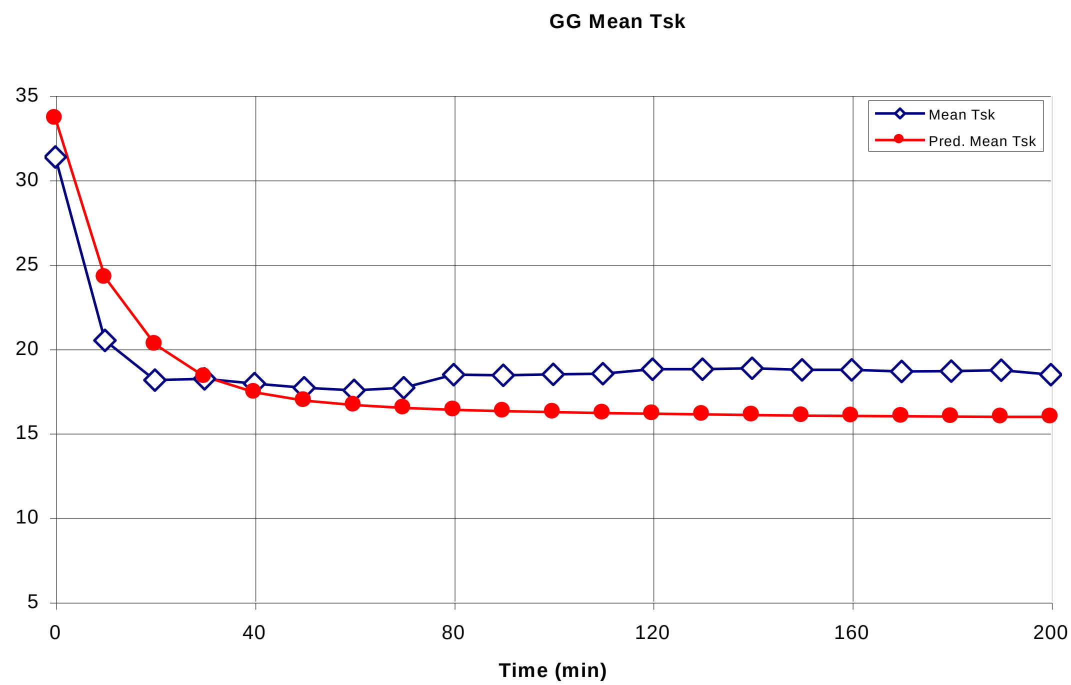
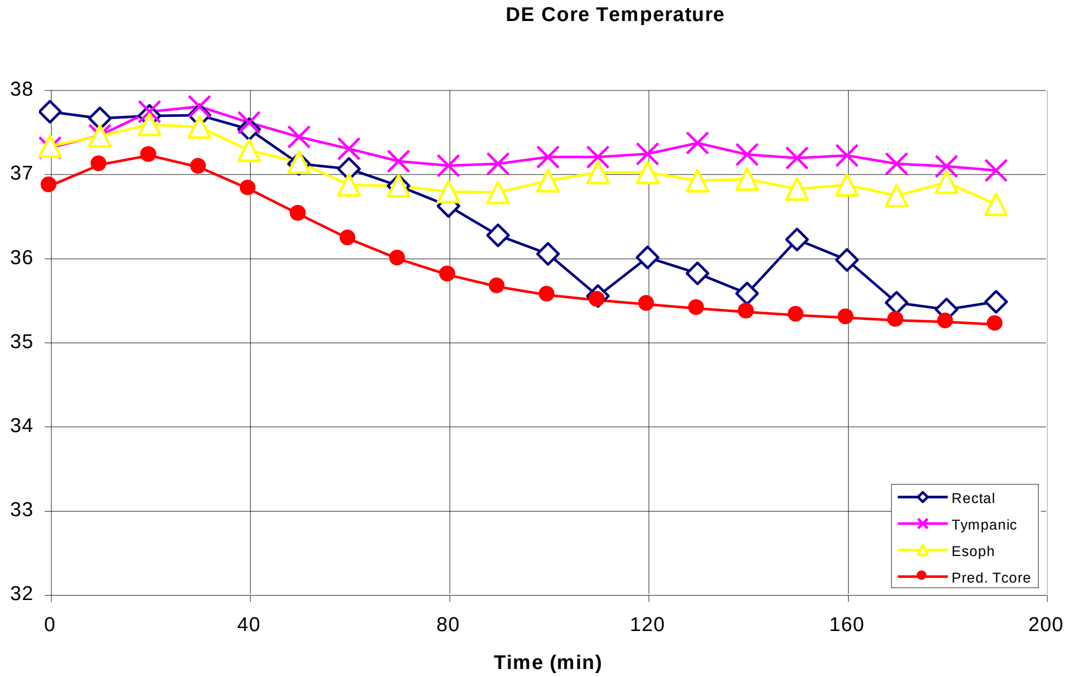


Figure 5. Experimental and predicted results during immersion in 10°C water for GG, Age 40, Height 1.83m, Weight 83.3kg, Fat 23.4%, VO_{2max} 48.6 mlO_2/kg min



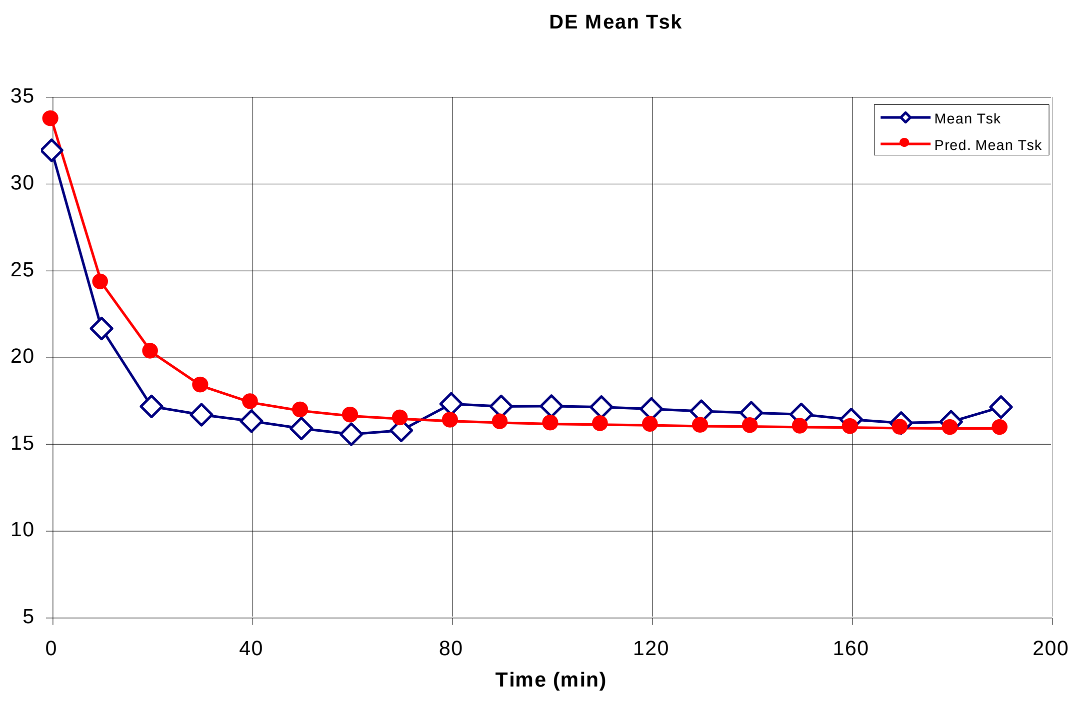
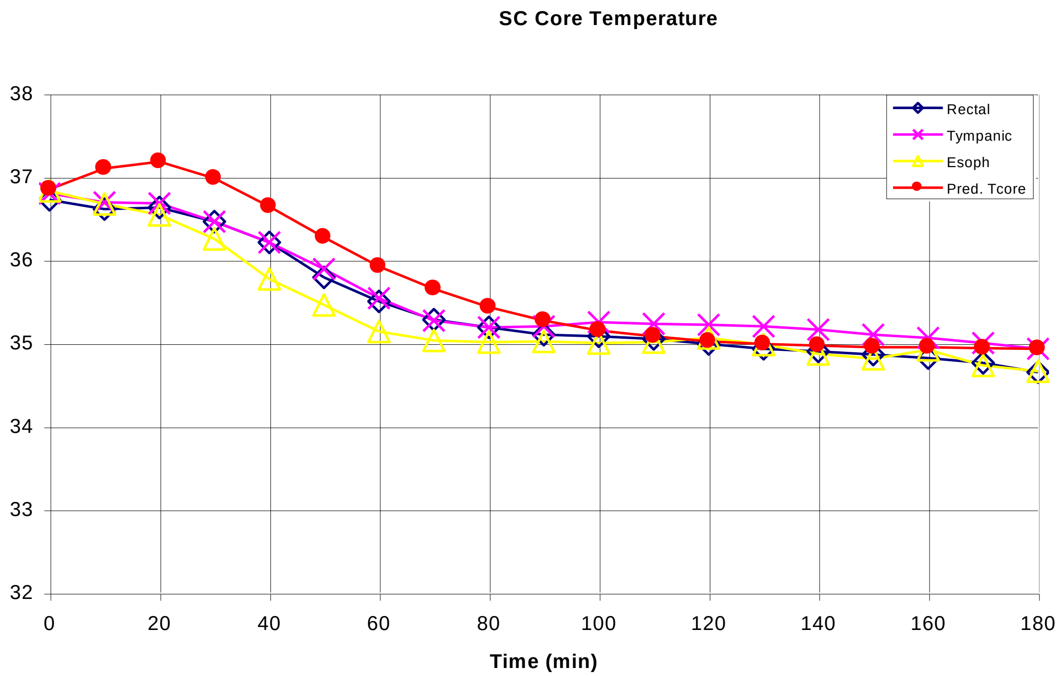


Figure 6. Experimental and predicted results during immersion in 10°C water for DE, Age 34, Height 1.80m, Weight 70.0kg, Fat 26.7%, VO_{2max} 49.3 mlO_2/kg min



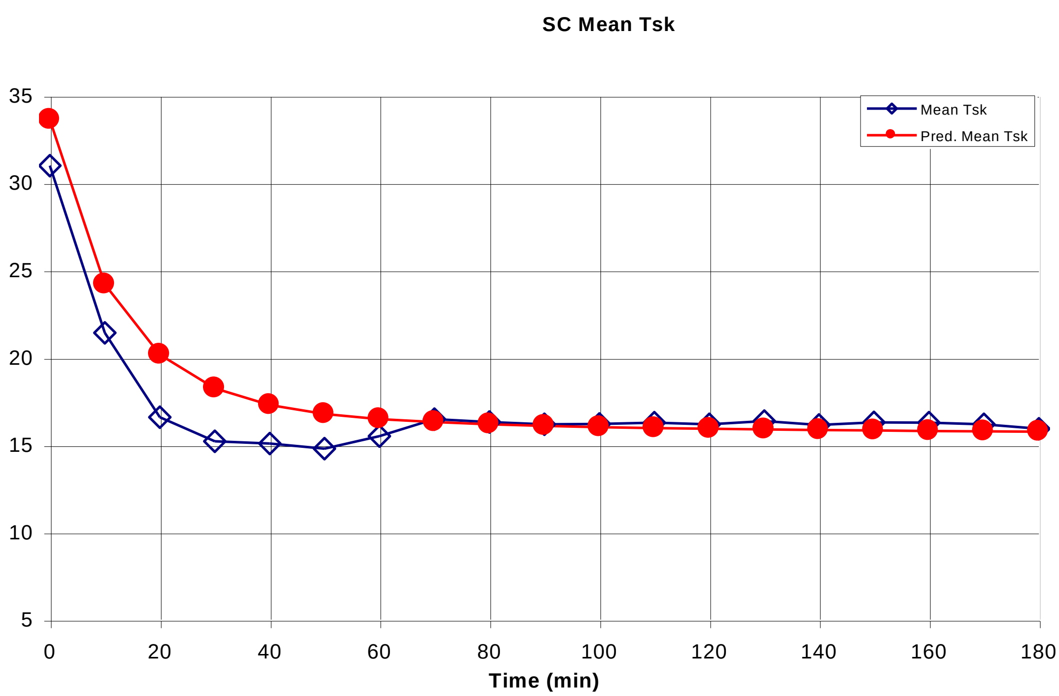
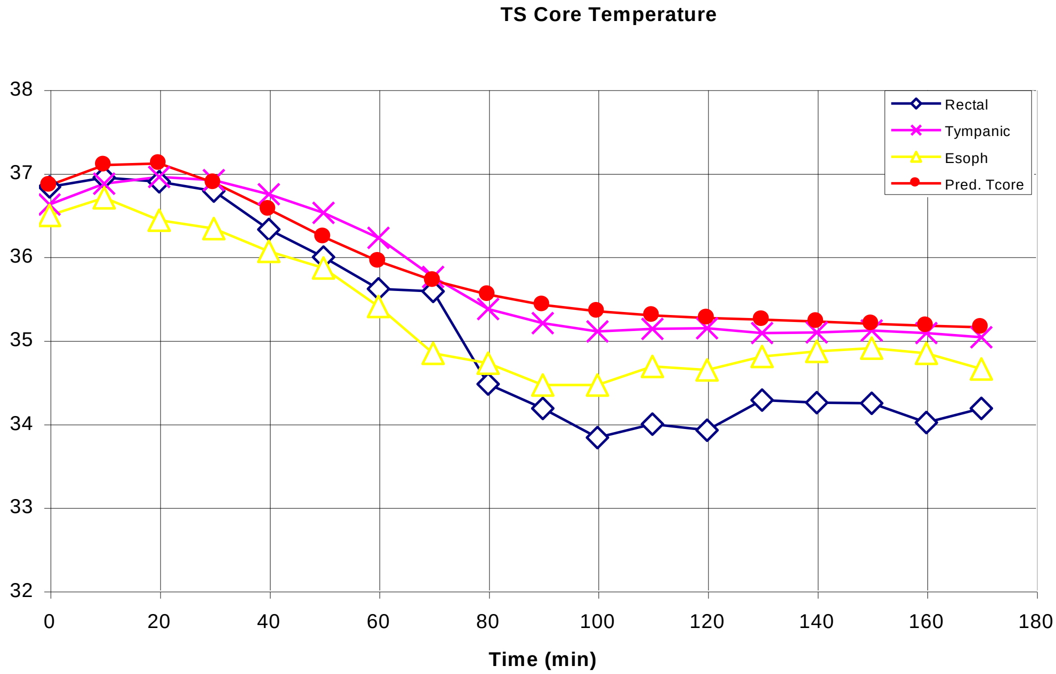


Figure 7. Experimental and predicted results during immersion in 10°C water for SC, Age 26, Height 1.61m, Weight 52.2kg, Fat 28.6%, VO_{2max} 53.6 mlO_2/kg min



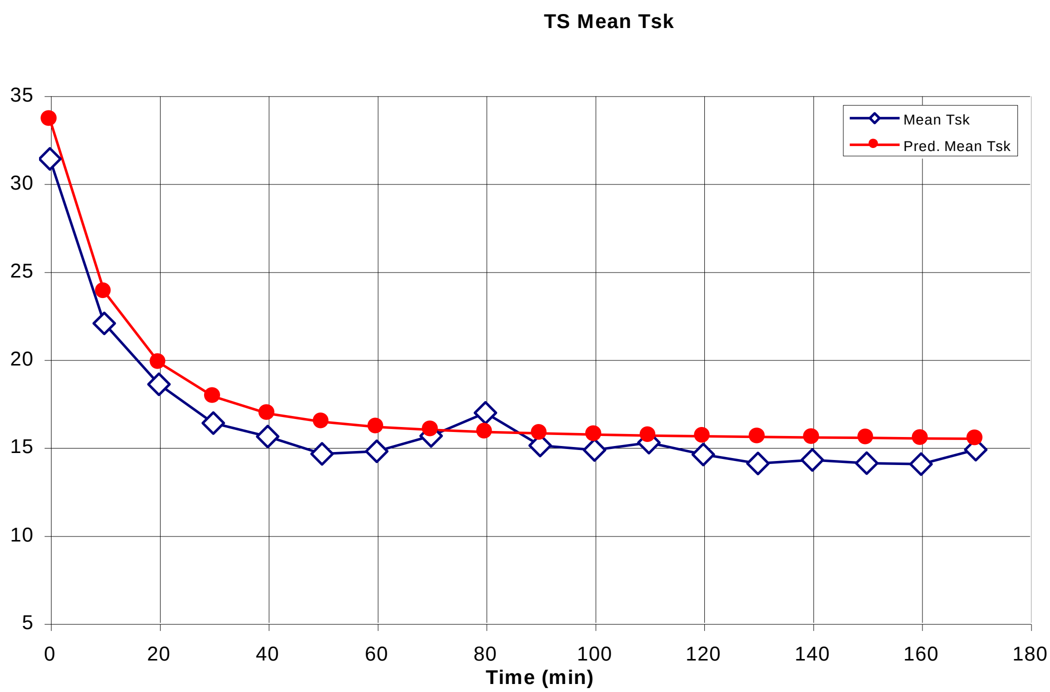
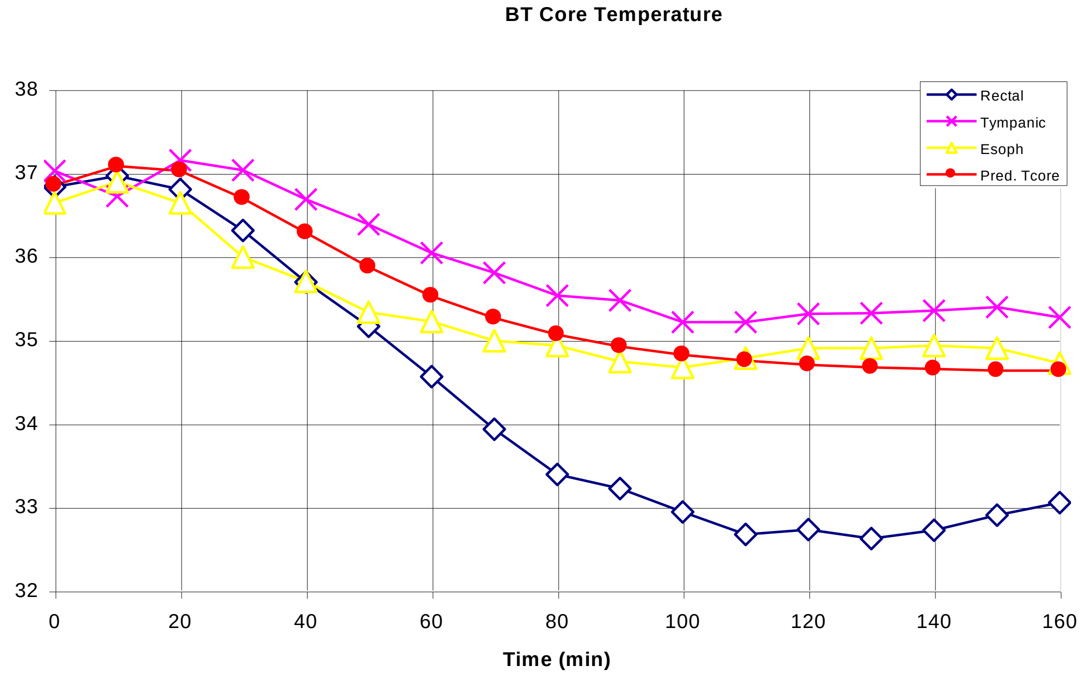


Figure 8. Experimental and predicted results during immersion in 9.0°C water for TS, Age 26, Height 1.84m, Weight 79.5kg, Fat 16.7%, VO_{2max} 64.5 mlO_2/kg min



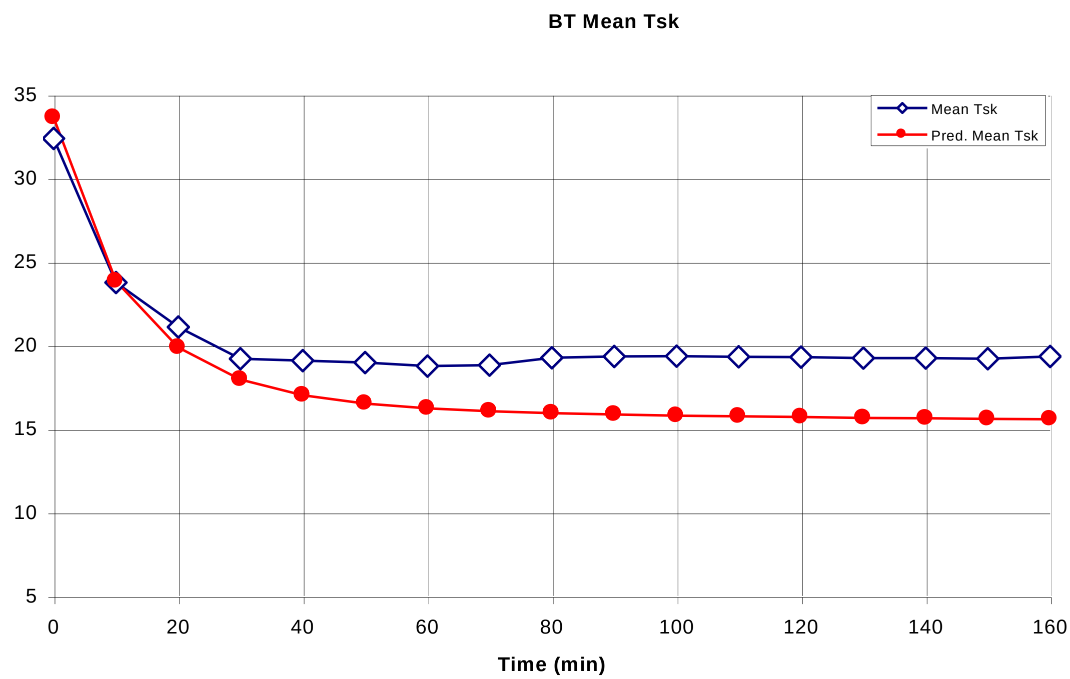
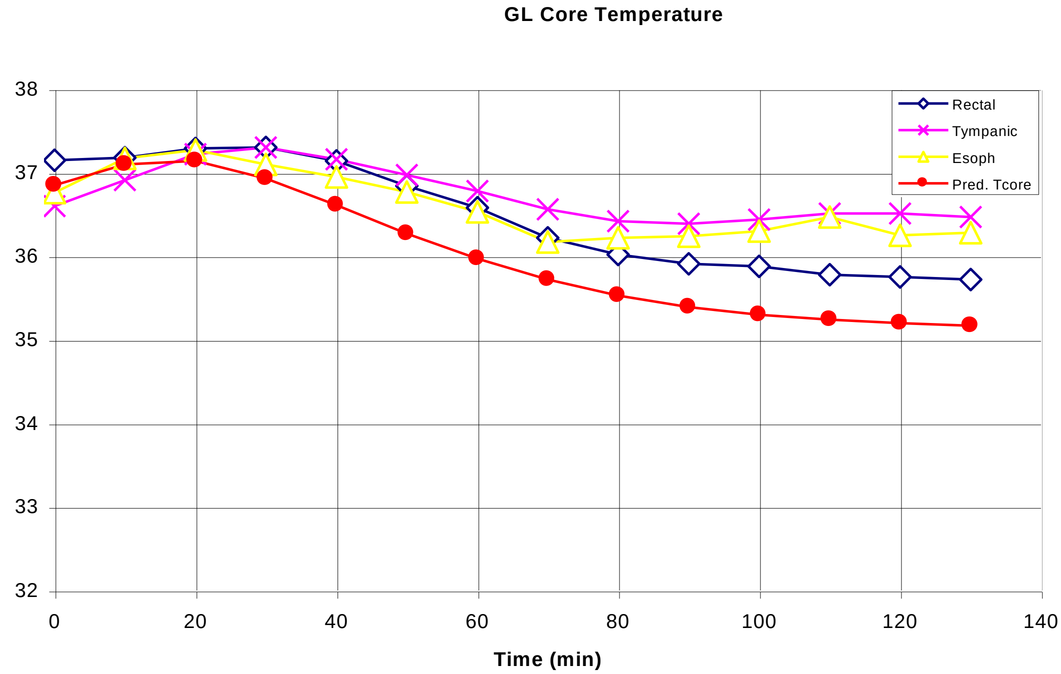


Figure 9. Experimental and predicted results during immersion in 9.0°C water for BT, Age 23, Height 1.65m, Weight 63.0kg, Fat 14.90%, VO_{2max} 55.8 mlO_2/kg min



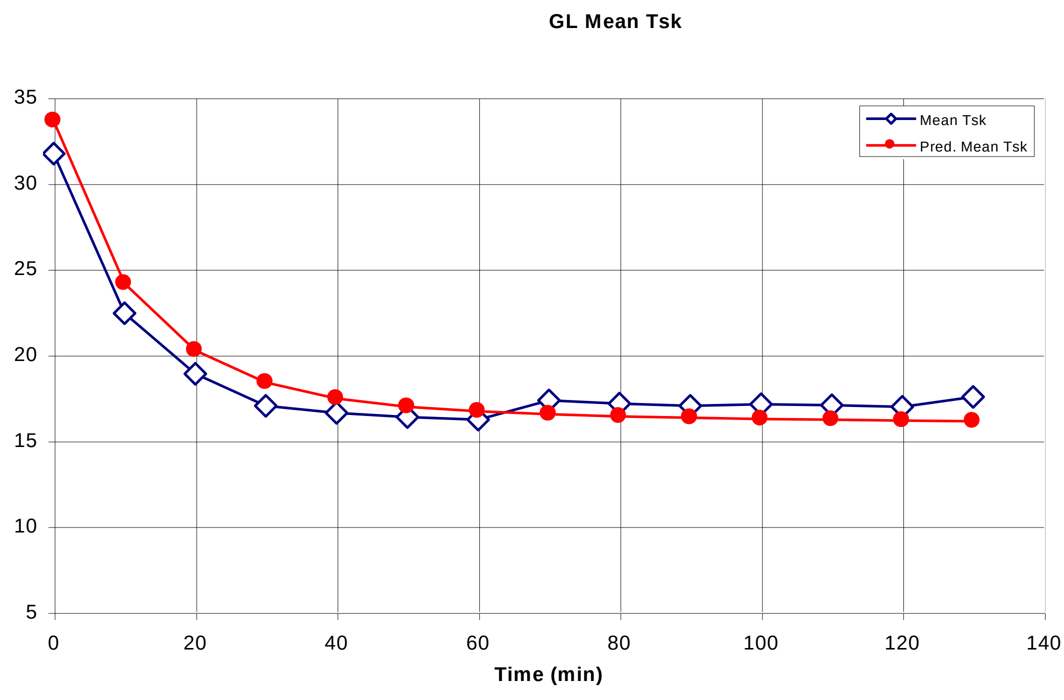
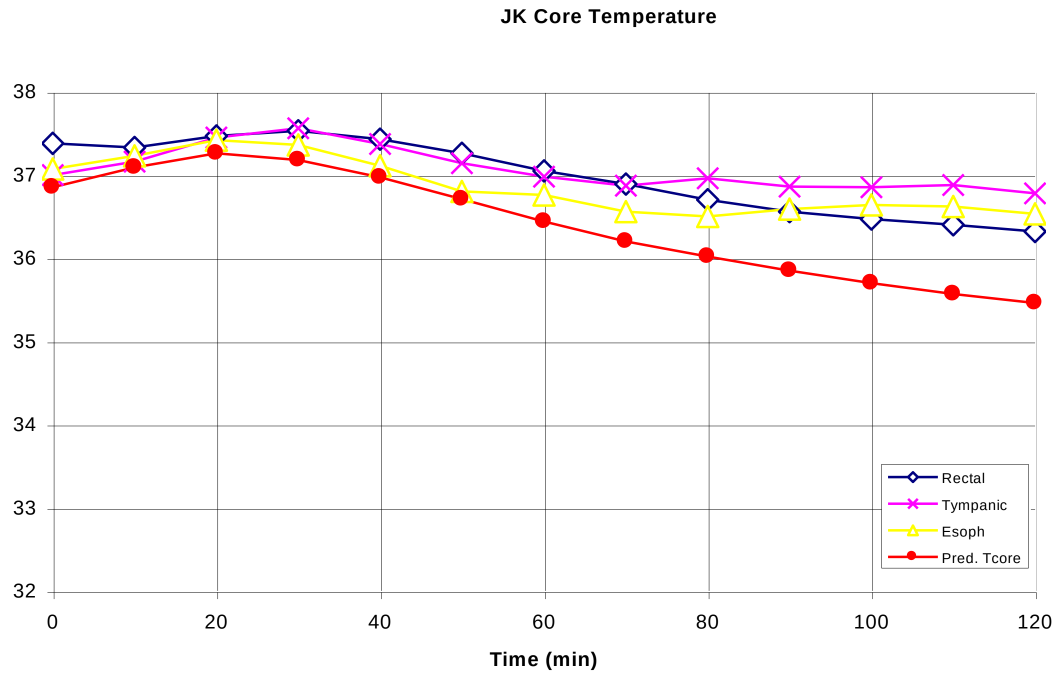


Figure 10. Experimental and predicted results during immersion in 10°C water for GL, Age 20, Height 1.82m, Weight 74.5kg, Fat 20.4%, VO_{2max} 52.8 mlO_2/kg min



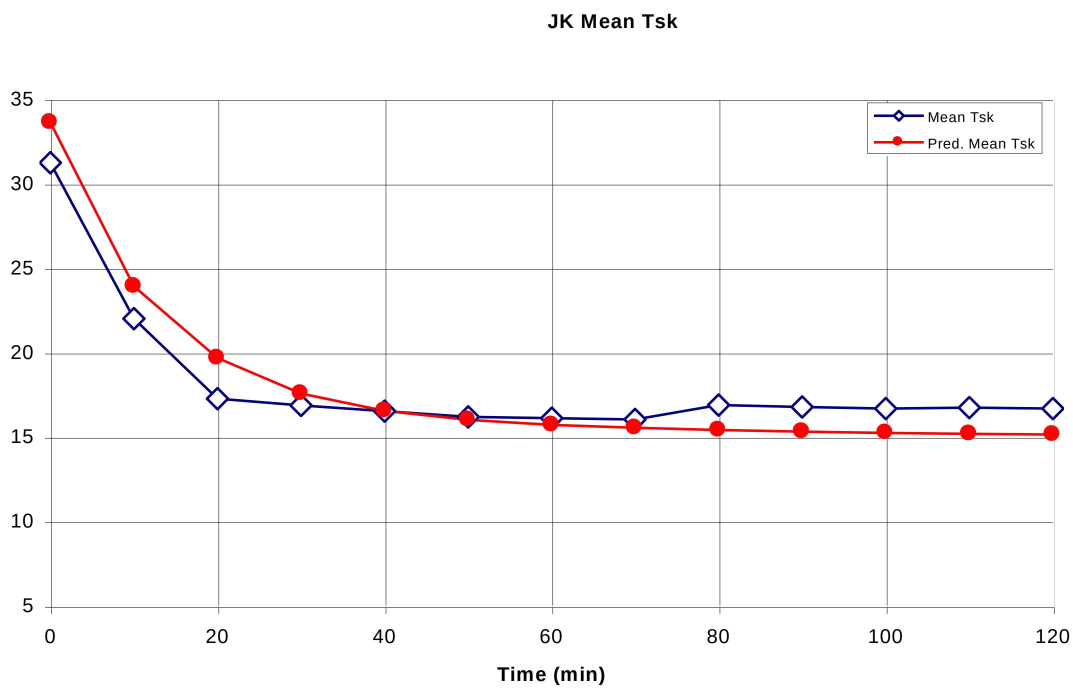


Figure 11. Experimental and predicted results during immersion in 10°C water for JK, Age 19, Height 1.72m, Weight 70.5kg, Fat 32.4%, VO_{2max} 44.4 mlO_2/kg min

AIR EXPOSURE DATA BASE

The experimental results were adopted from a study by Vallerand et al (1993). The experimental condition involved a 3 hour seated nude exposure at 5°C and a wind speed of about 1.0 m/s. The mean body characteristics of nine healthy subjects were 1.77m in height, 74.3kg body mass and 14% body fat. Because the VO_{2max} was not available, the current model used the default value that is 4.5 times of rest metabolic rate. After the 3h cold exposure, the rectal temperature rate was 36.5±0.3°C. The predicted core temperature is 35.7°C with a deviation of ±0.8°C. The drop in mean skin temperature over 3h exposure was about 4°C/h (0.07°C/min). Assuming that the mean skin temperature started with a value of 33°C prior to the cold exposure, it should be about 21°C at the end. The predicted mean skin temperature is 19.7°C and within a deviation of ±1.3°C. The measured metabolic heat production was about 145±15W/m^2 and predicted was 190 W/m^2.

ACCIDENT CASE - WATER SURVIVAL SCENARIO (VAN DORN, 2000)

Van Dorn (2000) described an accident and used the data for validation of his water survival model. A dive boat capsized and sank on Jan.1, 1990, off Guaymas, Mexico. Five survivors clung to a wooden door, four clad only in pajamas, and one (OW) in a full wet suit, which had fortuitously bobbed up beside him. A sixth survivor, VM clad in sweat shirt and levis and wearing a kapok life vest, swam for 35 hours in 16.7°C water to intercept the Guaymas-Sta. Rosalia ferry, which alerted a rescue boat to the accident scene. It found only OW, the others having slipped away at intervals chronicled by OW’s diving watch.

The body characteristics available are height and weight. The default fat percentage is calculated from the height and weight in the model (Xu 1996). The predicted survival time is the time when the core temperature falls below 30°C. The body characteristics, observed and predicted survival time are shown in Table 3. As the model has not taken into account the effects of the wet clothing on heat loss, it is

assumed that they are nude. Except for the results from OW and JL, the predicted survival times are close to the observed ones and acceptable. OW's wet suit provided extra thermal insulation that kept him warm. This is not considered in the model yet. From JL and JR's body characteristics, i.e. height and weight, it is easily speculated that JL should have more fat, therefore the model would predict a longer survival time. However, in reality JL's survival time was shorter.

Table 3 Observed and predicted survival time for the dive boat accident

Name	Height, m	Weight, kg	Observed survival time hrs	Predicted survival time hrs
O W*	1.78	91	38	26.5
V M*	1.75	100	35	38.5
J R	1.83	83	14	14.25
J L	1.80	86	12	18.25
[a]J R	1.68	73	11	10.0
N M	1.64	68	9	7.25

* denotes final survivors

DISCUSSION

The present new conceptual model for shivering intensity combines a shivering predictive model (Tikuisis & Giesbrecht, 1999), a "glycogen-depletion" model (Wissler 1985), a shivering exhaustion model (Tikuisis 1995), and a model of maximal shivering intensity (Eyolfson et al, 2001). An important component required to simulate is the "glycogen-depletion" model which is not well undstood. Additionally, what happens to excess metabolic heat production when a core temperature falls below a certain temperature e.g. 35°C or after a long duration is also not clearly understood.

A recent study by Tikuisis (2002) has demonstrated that the prediction from the "glycogen-depletion" model is satisfactory in comparison with observation during the water immersion test. In the dive boat accident, the model prediction showed that the survivors were able to maintain a heat balance for a period and the core temperature started to drop after the shivering "fatigue" appeared and metabolic heat production started to decrease. The predicted survival times are close to the observed for 4 of 6

survivors. Thus, the “glycogen-depletion” model seems to be provisionally satisfactory under certain modeling simulation circumstances.

Van Dorn (2000) developed a model using a first principles approach analyzing heat exchange during cold water survival that predicts survival time as a function of water temperature, assuming constant metabolic heat production and no blood flow convective heat transfer. Tikuisis (1995, 1997) developed a more complex thermodynamic model to predict survival time for cold exposure, taking the shivering exhaustion into account, but without blood flow convective heat transfer. Both these models provide estimations for the core temperature or survival time, and Tikuisis’s model predicts the casualty outcome of the accident case reasonable well (private communication, 2003). However, the six-cylinder model, which considers physiological and biophysical processes within the body and between the body surface and environments, could provide more power to simulate human thermal responses to cold environments and enables a better insight into thermoregulatory and heat balance mechanisms during cold exposure, particularly for working soldiers exposed to intermittent water/land walks.

The distributions of shivering metabolic heat production and blood flow in different components of the body, i.e. core, muscle, fat and skin of the six cylinders affect heat balance in the body during cold exposure. With the present model it is possible to simulate how and to what extent these distributions could influence the heat balance status of the body and how and to what extent different heat transfer avenues could contribute to it.

The human body regulates shivering heat production and vasomotor activities to maintain its heat balance status. The goal is to keep the core warm and stable. There is no clear definition yet what is included in the core, but it should compose some viscera in the torso, the brain also with blood constituents. The factors which could contribute to the core temperature response, are likely those in the torso such as metabolic heat production as well as the fat and muscle mass. A study by Bell et al. (1992)

demonstrated that about 75% of increased metabolic rate was produced in the torso. The shivering heat production in the extremities, e.g. legs and arms seems unlikely to be beneficial to the maintenance of the core temperature for the following reasons: 1) the heat conduction from extremities to the core to the ambient is minimal due to the low heat conductivity of tissues; 2) the temperature of the venous blood returning from extremities to the core would be low, as the tissue temperature could be reduced rapidly due to its physical shape and size; 3) shivering demands more blood flow to muscle, the perfused muscle thereby facilitates heat conduction. Therefore, the redistribution of blood from the extremities and from the cutaneous and peripheral vasculature to more central locations (i.e. core) plays a critical role in preserveing the heat within the core and diminishing heat loss to the environment.

The external heat transfer coefficient affects heat loss from the body surface to the environment, especially in the water. Its value in water can be about 25 times as high as in air. The convective heat transfer coefficients in water vary from 42 W/m^2°C (Boutelier et al 1977) for a resting subject in still water to 580 W/m^2°C (Nadel et al 1974) for a swimming subject in moving water. The results from a manikin vary from 137 W/m^2°C in still water to 1434 W/m^2°C in moving water (Witherspoon et al 1970). The differences in the reported convective heat transfer coefficients are likely due to body shape, positions, water velocity, and measurement technique used. In this model, the defaults for the convective heat transfer coefficient are 460W/m^2°C for the resting individuals in water and 580W/m^2°C for swimming person (Nadel et al 1974). For the water immersion tests, the convective heat transfer coefficients were measured. The average values varied from185.0 W/m^2°C for the torso, and 234 W/m^2°C for the leg and the foot. The heat transfer coefficients vary over wide range, and their potential influence needs to be considered when the model is applied for mixed land/water simulations.

This model uses height, weight, body fat, age, and VO_{2max} as individual characteristics. The validation against the results from the water immersion experiments

and the accident case showed that the overall agreement between observed and predicted results appear close and reasonable. However, the way that these individual characteristics were considered in the model requires further implicit analysis. Additional effort is being directed to identify what are the important individual characteristics and to establish relations between these characteristics and individual thermal responses.

CONCLUSIONS

In conclusion, a model for control of shivering intensity was conceptualized and incorporated into a six-cylinder model of human temperature regulation. This model is applicable to various operational scenarios relevant to OFW. In this current model, validation against results of the prolonged water immersion test showed that the model predictions are reliable within a root mean square deviation of ±0.8C° for the core temperature, ±1.9°C for the mean skin temperature, and ±47.2W for the metabolic rate, respectively.

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